CLAIMS

1. A method for use in a wireless communication system, the method comprising:

outputting at least one signal suitable for causing a smart antenna to transmit at least one complementary beam.

2. The method as recited in Claim 1, further comprising:

causing said smart antenna to transmit said at least one complementary beam based on said at least one signal.

3. The method as recited in Claim 2, wherein said at least one signal is operatively configured to cause said smart antenna to perform single beam complementary beamforming (SBCBF).

4. The method as recited in Claim 3, further comprising:

configuring said at least one signal to cause said smart antenna to perform said SBCBF by transmitting energy at a detectable transmit power level in all smart antenna-supported directions while substantially preserving a shape of at least one main transmit beam having a transmit power level that is significantly greater than said detectable transmit power level.

5. The method as recited in Claim 4, wherein said SBCBF is operatively performed by said smart antenna that is operatively associated with a base station within a wireless communication system.

6. The method as recited in Claim 5, wherein said base station includes a Butler matrix network configured to form said at least one main beam using said smart antenna.

7. The method as recited in Claim 6, wherein said Butler matrix network is configured to provide post-combining SBCBF.

8. The method as recited in Claim 6, wherein said Butler matrix network is configured to provide pre-combining SBCBF.

9. The method as recited in Claim 1, wherein said at least one signal is operatively configured to cause said smart antenna to perform subspace complementary beamforming (SCBF).

10. The method as recited in Claim 9, further comprising:

determining said at least one signal by selectively modifying a weight matrix to operatively support said SCBF.

11. The method as recited in Claim 9, further comprising:

determining said at least one signal by selectively expanding a size of a weight matrix to operatively support said SCBF.

12. The method as recited in Claim 9, wherein said at least one signal includes *N-K* data streams operatively configured to cause said smart antenna to transmit energy in at least one side lobe.

13. The method as recited in Claim 9, further comprising:

determining said at least one signal by using a Downlink Beamforming Matrix : $\boldsymbol{W} = \boldsymbol{U}\boldsymbol{\Lambda}\boldsymbol{V}^H$.

14. The method as recited in Claim 9, further comprising:

determining said at least one signal by using a Steering Matrix: $\boldsymbol{A} = [\boldsymbol{a}(\theta_1) \quad \boldsymbol{a}(\theta_2) \quad \cdots \quad \boldsymbol{a}(\theta_K)]$, wherein $\boldsymbol{a}(\theta_k)$ represents a steering vector of user k.

15. The method as recited in Claim 14, wherein:

if $\boldsymbol{W} = \boldsymbol{A}^* \boldsymbol{B}$, where B is a non-singular K-by-K matrix, then using a complementary beamforming matrix of

$$\boldsymbol{W}^c = \sqrt{\frac{k_0 C_0}{N}} [\boldsymbol{u}_{K+1} \quad \boldsymbol{u}_{K+2} \quad \cdots \quad \boldsymbol{u}_N]$$

wherein $C_0 = Nc_0$ is the level of the main lobe, k_0 is the scaling factor and $\boldsymbol{u}_l$ is the l-th column vector of $\boldsymbol{U}$,

otherwise using a complementary beamforming matrix of

$$\boldsymbol{W}^c = \sqrt{\frac{k_0 C_0}{N}} [\overline{\boldsymbol{u}}_1 \quad \overline{\boldsymbol{u}}_2 \quad \cdots \quad \overline{\boldsymbol{u}}_{N-K}]$$

wherein $\overline{\boldsymbol{u}}_l$ is the l-th left singular vector of the matrix

$\left(\sum_{l=K+1}^{N} \tilde{\boldsymbol{u}}_l \tilde{\boldsymbol{u}}_l^H \right) \boldsymbol{U}\boldsymbol{\Lambda}^c = \overline{\boldsymbol{U}}\overline{\boldsymbol{\Lambda}}\overline{\boldsymbol{V}}^H$, and $\boldsymbol{A}^* = \tilde{\boldsymbol{U}}\tilde{\boldsymbol{\Lambda}}\tilde{\boldsymbol{V}}^H$ is assumed, and in scattering channel $\boldsymbol{H}^* = \tilde{\boldsymbol{U}}\tilde{\boldsymbol{\Lambda}}\tilde{\boldsymbol{V}}^H$ is assumed.

16. The method as recited in Claim 15, wherein it is assumed that $2K<N$,

$$W_a = [W \quad A^*] = U_a \Lambda_a V_a^H \text{, and } W^c = \sqrt{\frac{k_0 C_0}{N}} [u_{a,r+1} \quad u_{a,r+2} \quad \cdots \quad u_{a,N}],$$

and wherein r is rank of W_a.

17. The method as recited in Claim 1, wherein said at least one signal is operatively configured to cause said smart antenna to perform complementary superposition beamforming (CSBF).

18. The method as recited in Claim 17, further comprising:

determining said at least one signal by using a downlink beamforming matrix : $\tilde{W} = [w_1 \quad \cdots \quad w_{k-1} \quad \tilde{w}_k \quad w_{k+1} \quad \cdots \quad w_K]$, where $\tilde{w}_k = p_0 w_k + W^c p$ and p is complex conjugate transpose of the l-th row of W^c, $p_0 = \frac{w_{k,l}^*}{|w_{k,l}|}$ is normalized complex conjugate of the l-th element of w_k.

19. The method as recited in Claim 18, wherein W^c is associated with subspace complementary beamforming (SCBF).

20. The method as recited in Claim 17, further comprising:

determining said at least one signal by using $\tilde{W} = [w_1 \quad w_2 \quad \cdots \quad w_K \quad W^c p]$.

21. The method as recited in Claim 17, further comprising:

determining said at least one signal by using a null-generation technique that is configured to generate L nulls at angles $\theta_1, \theta_2, \cdots, \theta_L$ at a beam.

22. The method as recited in Claim 17, further comprising:

determining said at least one signal by using $\boldsymbol{A} = [\boldsymbol{a}(\theta_1) \quad \boldsymbol{a}(\theta_2) \quad \cdots \quad \boldsymbol{a}(\theta_L)]$.

23. The method as recited in Claim 17, further comprising:

determining said at least one signal by projecting $\boldsymbol{w}$ onto orthogonal complement subspace of column space $\boldsymbol{A}^*$.

24. The method as recited in Claim 17, further comprising:

determining said at least one signal by using a vector : $\boldsymbol{w} = (\boldsymbol{I} - \boldsymbol{P}_S)\boldsymbol{w}$ where $\boldsymbol{P}_S = \boldsymbol{A}^*(\boldsymbol{A}^T\boldsymbol{A}^*)^{-1}\boldsymbol{A}^T$, and in scattering channel $\boldsymbol{P}_S = \boldsymbol{H}^*(\boldsymbol{H}^T\boldsymbol{H}^*)^{-1}\boldsymbol{H}^T$.

25. The method as recited in Claim 17, further comprising:

determining said at least one signal by using a null-widening technique that is configured to produce at least one null at a vicinity of selected angles.

26. The method as recited in Claim 17, further comprising:

determining said at least one signal by selectively modifying a steering matrix to:

$$A = [\tilde{\boldsymbol{a}}(\theta_1) \quad \tilde{\boldsymbol{a}}(\theta_2) \quad \cdots \quad \tilde{\boldsymbol{a}}(\theta_K)]$$

wherein $\tilde{\boldsymbol{a}}(\theta_k) = [\boldsymbol{a}(\theta_k - \Delta\theta_l) \quad \boldsymbol{a}(\theta_k) \quad \boldsymbol{a}(\theta_k + \Delta\theta_r)]$.

27. The method as recited in Claim 17, further comprising:

determining said at least one signal by establishing at least two nulls such that a rank of A is less than N.

28. The method as recited in Claim 17, further comprising:

determining said at least one signal by using adaptive control of a complementary beam level.

29. The method as recited in Claim 17, further comprising:

determining said at least one signal by, in a non-zero angular channel, selectively reducing a complementary beam level.

30. The method as recited in Claim 17, further comprising:

determining said at least one signal by, for delay spread channels, selectively reducing a complementary beam level.

31. The method as recited in Claim 17, further comprising:

determining said at least one signal by, in free space, selectively increasing the complementary beam level.

32. The method as recited in Claim 1, wherein outputting said at least one signal suitable for causing said smart antenna to transmit at least one complementary beam further includes:

using a zero-forcing beamformer to output said at least one signal.

33. The method as recited in Claim 1, wherein outputting said at least one signal suitable for causing said smart antenna to transmit at least one complementary beam further includes:

using a maximum SINR beamformer to output said at least one signal.

34. The method as recited in Claim 1, wherein outputting said at least one signal suitable for causing said smart antenna to transmit at least one complementary beam further includes:

selectively constructing a plurality of matrices Z_1, Z_1, …, Z_L, where L is a length of a downlink transmission period, such that said plurality of matrices satisfy at least one property selected from a group of properties comprising:

(a) for all $1 \leq i \leq L$, a matrix Z_i is a $k \times m$ matrix whose rows are in a set $\{0, \pm U_0^H, \pm U_1^H, \ldots, \pm U_{m-k-1}^H\}$;

(b) if L is even, then, $Z_2 = -Z_1$, $Z_4 = -Z_3$, …, $Z_L = -Z_{L-1}$;

(c) if L is odd, then $Z_2 = -Z_1$, $Z_4 = -Z_3$, …, $Z_{L-1} = -Z_{L-2}$, $Z_L = 0$;

and

(d) each element $+U_0^H$, $-U_0^H$, $+U_1^H$, $-U_1^H$, …, $+U_{m-k-1}^H$, $-U_{m-k-1}^H$ appear p times in a list of Lk rows of Z_1, Z_1, …, Z_L for some positive integer p.

35. The method as recited in Claim 34, wherein rows of Z_{2i-1} are, respectively, $U_{0\oplus i}^H$, $U_{1\oplus i}^H$, …, $U_{k-1\oplus i}^H$ and where $i \oplus j$ denote $(i + j) \bmod (m - k)$ for $i =$ 1, 2, 3, …, $[L/2]$ and wherein $Z_{2i} = -Z_{2i-1}$.

36. The method as recited in Claim 34, further comprising:

using as a beamforming matrix:

$$S' = \left[\left(A^H A\right)^{-1} A^H / \sqrt{Tr\left(\left(A^H A\right)^{-1}\right)} + \frac{1}{\sqrt{k}} \varepsilon Z_i \right]$$

where $\varepsilon \geq 0$ is a fixed positive number.

37. The method as recited in Claim 36, wherein said complementary beam is configured to cause a loss of at most $10 \log_{10}\left(1+|\varepsilon|^2\right)$ in a received signal for an intended recipient.

38. The method as recited in Claim 36, wherein said complementary beam is configured to direct a portion:

$$|\varepsilon|^2 \frac{\sum_{j=1}^{m} |b_j|^2}{m}$$

of a resulting transmitted power to another recipient whose spatial signature is $B=(b_1,b_2,\ldots,b_m)$.

39. The method as recited in Claim 1, wherein outputting said at least one signal suitable for causing said smart antenna to transmit at least one complementary beam further includes:

outputting said signal based on at least a complementary beamforming matrix at time t given by:

$$S' = \left[\left(A^H A\right)^{-1} A^H / \sqrt{Tr\left(\left(A^H A\right)^{-1}\right)} + \frac{1}{\sqrt{k}} \varepsilon Z_t \right].$$

40. The method as recited in Claim 1, wherein outputting said at least one signal suitable for causing said smart antenna to transmit at least one complementary beam further includes:

outputting said signal based on at least matrices $P_0, P_1, \ldots, P_{m-k}$ having rows, respectively, $U_0^H, U_1^H, \ldots, U_{m-k}^H$ and wherein a fixed beamforming matrix is given by:

$$S = \left[\left(A^H A\right)^{-1} A^H / \sqrt{Tr\left(\left(A^H A\right)^{-1}\right)} + \frac{1}{\sqrt{k}} \varepsilon \sum_{i=1}^{m-k} P_i \right].$$

41. An apparatus for use in a wireless communication system, the apparatus comprising:

circuitry configured to output at least one signal suitable for causing a smart antenna to transmit at least one complementary beam.

42. The apparatus as recited in Claim 41, further comprising:

a smart antenna operatively coupled to receive said at least one signal and configured to transmit said at least one complementary beam based on said at least one signal.

43. The apparatus as recited in Claim 42, wherein said at least one signal is operatively configured to cause said smart antenna to perform single beam complementary beamforming (SBCBF).

44. The apparatus as recited in Claim 43, wherein said at least one signal is configured by said circuitry to cause said smart antenna to perform said SBCBF

by transmitting energy at a detectable transmit power level in all smart antenna-supported directions while substantially preserving a shape of at least one main transmit beam having a transmit power level that is significantly greater than said detectable transmit power level.

45. The apparatus as recited in Claim 44, wherein said SBCBF is operatively performed by said smart antenna that is operatively associated with a base station within a wireless communication system, said base station including at least a portion of said circuity.

46. The apparatus as recited in Claim 45, wherein said circuitry includes a Butler matrix network configured to form said at least one main beam using said smart antenna.

47. The apparatus as recited in Claim 46, wherein said Butler matrix network is configured to provide post-combining SBCBF.

48. The apparatus as recited in Claim 46, wherein said Butler matrix network is configured to provide pre-combining SBCBF.

49. The apparatus as recited in Claim 41, wherein said at least one signal is operatively configured to cause said smart antenna to perform subspace complementary beamforming (SCBF).

50. The apparatus as recited in Claim 49, wherein said circuitry is configured to determine said at least one signal by selectively modifying a weight matrix to operatively support said SCBF.

51. The apparatus as recited in Claim 49, wherein said circuitry is configured to determine said at least one signal by selectively expanding a size of a weight matrix to operatively support said SCBF.

52. The apparatus as recited in Claim 49, wherein said at least one signal includes *N-K* data streams operatively configured to cause said smart antenna to transmit energy in at least one side lobe.

53. The apparatus as recited in Claim 49, wherein said circuitry is configured to determine said at least one signal by using a Downlink Beamforming Matrix : $\boldsymbol{W} = \boldsymbol{U}\boldsymbol{\Lambda}\boldsymbol{V}^H$.

54. The apparatus as recited in Claim 49, wherein said circuitry is configured to determine said at least one signal by using a Steering Matrix: $\boldsymbol{A} = [\boldsymbol{a}(\theta_1) \quad \boldsymbol{a}(\theta_2) \quad \cdots \quad \boldsymbol{a}(\theta_K)]$, wherein $\boldsymbol{a}(\theta_k)$ represents a steering vector of user k.

55. The apparatus as recited in Claim 54, wherein:

if $\boldsymbol{W} = \boldsymbol{A}^*\boldsymbol{B}$, where B is a non-singular K-by-K matrix, then said circuitry is configured to use a complementary beamforming matrix of

$$\boldsymbol{W}^c = \sqrt{\frac{k_0 C_0}{N}}[\boldsymbol{u}_{K+1} \quad \boldsymbol{u}_{K+2} \quad \cdots \quad \boldsymbol{u}_N]$$

wherein $C_0 = Nc_0$ is the level of the main lobe, k_0 is the scaling factor and $\boldsymbol{u}_l$ is the l-th column vector of $\boldsymbol{U}$,

otherwise said circuitry is configured to use a complementary beamforming matrix of

$$\boldsymbol{W}^c = \sqrt{\frac{k_0 C_0}{N}} \begin{bmatrix} \overline{\boldsymbol{u}}_1 & \overline{\boldsymbol{u}}_2 & \cdots & \overline{\boldsymbol{u}}_{N-K} \end{bmatrix}$$

wherein $\overline{\boldsymbol{u}}_l$ is the l-th left singular vector of the matrix

$\left(\sum_{l=K+1}^{N} \tilde{\boldsymbol{u}}_l \tilde{\boldsymbol{u}}_l^H \right) \boldsymbol{U}\boldsymbol{\Lambda}^c = \overline{\boldsymbol{U}}\overline{\boldsymbol{\Lambda}}\overline{\boldsymbol{V}}^H$, and $\boldsymbol{A}^* = \tilde{\boldsymbol{U}}\tilde{\boldsymbol{\Lambda}}\tilde{\boldsymbol{V}}^H$ is assumed, and in scattering channel $\boldsymbol{H}^* = \tilde{\boldsymbol{U}}\tilde{\boldsymbol{\Lambda}}\tilde{\boldsymbol{V}}^H$ is assumed.

56. The apparatus as recited in Claim 55, wherein said circuitry is configured such that $2K<N$,

$$\boldsymbol{W}_a = \begin{bmatrix} \boldsymbol{W} & \boldsymbol{A}^* \end{bmatrix} = \boldsymbol{U}_a \boldsymbol{\Lambda}_a \boldsymbol{V}_a^H, \text{ and } \boldsymbol{W}^c = \sqrt{\frac{k_0 C_0}{N}} \begin{bmatrix} \boldsymbol{u}_{a,r+1} & \boldsymbol{u}_{a,r+2} & \cdots & \boldsymbol{u}_{a,N} \end{bmatrix},$$

and wherein r is rank of $\boldsymbol{W}_a$.

57. The apparatus as recited in Claim 41, wherein said circuitry is configured such that said at least one signal causes said smart antenna to perform complementary superposition beamforming (CSBF).

58. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by using a downlink beamforming matrix : $\tilde{W} = [w_1 \ \cdots \ w_{k-1} \ \tilde{w}_k \ w_{k+1} \ \cdots \ w_K]$, where $\tilde{w}_k = p_0 w_k + W^c p$ and p is complex conjugate transpose of the l-th row of W^c, $p_0 = \frac{w^*_{k,l}}{|w_{k,l}|}$ is normalized complex conjugate of the l-th element of w_k.

59. The apparatus as recited in Claim 58, wherein W^c is associated with subspace complementary beamforming (SCBF).

60. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by using $\tilde{W} = [w_1 \ w_2 \ \cdots \ w_K \ W^c p]$.

61. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by using a null-generation technique that is configured to generate L nulls at angles $\theta_1, \theta_2, \cdots, \theta_L$ at a beam.

62. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by using $A = [a(\theta_1) \ a(\theta_2) \ \cdots \ a(\theta_L)]$.

63. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by projecting w onto orthogonal complement subspace of column space A^*.

64. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by using a vector : $w = (I - P_S)w$ where $P_S = A^*(A^T A^*)^{-1} A^T$, and in scattering channel $P_S = H^*(H^T H^*)^{-1} H^T$.

65. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by using a null-widening technique that is configured to produce at least one null at a vicinity of selected angles.

66. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by selectively modifying a steering matrix to:

$$A = [\tilde{a}(\theta_1) \quad \tilde{a}(\theta_2) \quad \cdots \quad \tilde{a}(\theta_K)]$$

wherein $\tilde{a}(\theta_k) = [a(\theta_k - \Delta\theta_l) \quad a(\theta_k) \quad a(\theta_k + \Delta\theta_r)]$.

67. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by establishing at least two nulls such that a rank of A is less than N.

68. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by using adaptive control of a complementary beam level.

69. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by, in a non-zero angular channel, selectively reducing a complementary beam level.

70. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by, for delay spread channels, selectively reducing a complementary beam level.

71. The apparatus as recited in Claim 57, wherein said circuitry is configured to determine said at least one signal by, in free space, selectively increasing the complementary beam level.

72. The apparatus as recited in Claim 41, wherein said circuitry employs a zero-forcing beamformer to output said at least one signal.

73. The apparatus as recited in Claim 41, wherein said circuitry employs a maximum SINR beamformer to output said at least one signal.

74. The apparatus as recited in Claim 41, wherein said circuitry is configured to construct a plurality of matrices Z_1, Z_1, …, Z_L, where L is a length of a downlink transmission period, such that said plurality of matrices satisfy at least one property selected from a group of properties comprising:

(a) for all $1 \le i \le L$, a matrix Z_i is a $k \times m$ matrix whose rows are in a set $\{0, \pm U_0^H, \pm U_1^H, \ldots, \pm U_{m-k-1}^H\}$;

(b) if L is even, then, $Z_2 = -Z_1$, $Z_4 = -Z_3$, …, $Z_L = -Z_{L-1}$;

(c) if L is odd, then $Z_2 = -Z_1$, $Z_4 = -Z_3$, …, $Z_{L-1} = -Z_{L-2}$, $Z_L = 0$;

and

(d) each element $+U_0^H$, $-U_0^H$, $+U_1^H$, $-U_1^H$, ..., $+U_{m-k-1}^H$, $-U_{m-k-1}^H$ appear p times in a list of Lk rows of Z_1, Z_1, ..., Z_L for some positive integer p.

75. The apparatus as recited in Claim 74, wherein rows of Z_{2i-1} are, respectively, $U_{0\oplus i}^H$, $U_{1\oplus i}^H$, ..., $U_{k-1\oplus i}^H$ and where $i\oplus j$ denote $(i + j)$ mod $(m - k)$ for i = 1, 2, 3, ..., $[L/2]$ and wherein $Z_{2i}=-Z_{2i-1}$.

76. The apparatus as recited in Claim 34, wherein said circuitry is configurted to construct a beamforming matrix:

$$S'=\left[\left(A^H A\right)^{-1} A^H / \sqrt{Tr\left(\left(A^H A\right)^{-1}\right)} + \frac{1}{\sqrt{k}} \varepsilon Z_i\right]$$

where $\varepsilon \geq 0$ is a fixed positive number.

77. The apparatus as recited in Claim 76, wherein said complementary beam is configured to cause a loss of at most $10 \log_{10}\left(1+|\varepsilon|^2\right)$ in a received signal for an intended recipient.

78. The apparatus as recited in Claim 76, wherein said complementary beam is configured to direct a portion:

$$|\varepsilon|^2 \frac{\sum_{j=1}^{m} |b_j|^2}{m}$$

of a resulting transmitted power to another recipient whose spatial signature is $B=(b_1, b_2, ..., b_m)$.

79. The apparatus as recited in Claim 41, wherein said circuitry is configured to output said signal based on at least a complementary beamforming matrix at time t given by:

$$S' = \left[\left(A^H A\right)^{-1} A^H / \sqrt{Tr\left(\left(A^H A\right)^{-1}\right)} + \frac{1}{\sqrt{k}} \varepsilon Z_t \right].$$

80. The apparatus as recited in Claim 41, wherein said circuitry is configured to output said signal based on at least matrices $P_0, P_1, \ldots, P_{m-k}$ having rows, respectively, $U_0^H, U_1^H, \ldots, U_{m-k}^H$ and wherein a fixed beamforming matrix that is used is given by:

$$S = \left[\left(A^H A\right)^{-1} A^H / \sqrt{Tr\left(\left(A^H A\right)^{-1}\right)} + \frac{1}{\sqrt{k}} \varepsilon \sum_{i=1}^{m-k} P_i \right].$$